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Chemical characterization of soil phosphorus and organic matter in different cropping systems in Maine, U.S.A.

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Abstract

To minimize purchased inputs, sustainable agriculture systems often use green- or animal-manure as a nitrogen source for crops. The addition of these materials also have positive impacts on soil phosphorus (P) availability. This study was conducted to investigate the effects of animal- and legume-based cropping systems in place for 5–13 years on the chemistry of organic matter and soil P. Two cropping systems, Potato Ecosystem (ECO) located in Presque Isle, ME, U.S.A. and Grass Fertility (GF) located in Stillwater, ME, U.S.A. received animal manure. Two others, Liebman E Rotation (LER) in Stillwater, ME, U.S.A. and Porter Rotation (PR) in Presque Isle, ME, U.S.A. were primarily legume-based rotations. Estimated difference in carbon input (ha^{-1} $year^{-1}$) between the amended and control plots were: ECO, 8100 kg C; GF, 1010 kg; LER, 950 kg C; and PR, 415 kg C. The dissolved organic carbon (DOC) concentration was higher ($P < 0.10$) in the treatment that received animal manure than those which only received legume residue. The E2/E3 spectrophotometric test indicated that the DOC extracted from the ECO manure-treated plots was more humified than that from the ECO control plots. There were no significant differences between the amended and control treatments in Olsen P or total P for all the tested cropping systems. Similar to that of the DOC response, the ECO cropping system that received animal manure recorded higher concentrations of water soluble P ($P < 0.05$). There was a linear relationship between DOC and water-soluble P concentrations of the soil:water extract across soils, indicating a positive relationship between them. To determine the effects of the different cropping systems on P bioavailability, a simulation model was used to study how changes in P soil chemistry may affect P uptake by crops. The simulation runs showed that predicted P uptake was greater for the animal manure based ECO and GF systems, but not for the legume based LER and PR systems ($P <$ 0.05). This study shows that cropping systems that include animal manure may increase soil P availability.

Keywords: Soil organic matter; Soil phosphorus; Simulation modeling; Animal manures; Green manures

1. Introduction

The low P-efficiency from fertilization is mostly due to P-fixation through adsorption or precipitation

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reactions in soils (Tisdale et al., 1993). The sparingly soluble nature of most soil P compounds makes it difficult to supply sufficient P to achieve high crop yields without adding additional inorganic P fertilizers (Lindsay, 1979). Although this practice can produce high yields, it can lead to eutrophication when P-rich soil particles erode from fields and reach surface waters (Higgs et al., 2000). Recent studies have suggested that eutrophication is the primary cause of diminished water quality in the United States (USEPA, 1996). Although agricultural land is clearly not the sole source of P involved in eutrophication, there is growing acceptance that agricultural activities such as fertilization and application of organic manure represent a significant source of P input to surface waters (Sharpley et al., 2000).

Concerns about increasing P loads in the environment, as well as reducing the quantity of purchased inputs, have driven efforts to develop alternative farming practices that can compensate for P fertilization. One potential approach is to adopt cropping systems that may increase the level of plant available P in soil. Cropping systems that utilize green and animal manures have been demonstrated to have a positive impact on crop yields and reduce dependency on chemical fertilizers (Karlen et al., 1994; Tisdale et al., 1993). Organic amendments can directly affect soil P through interaction with soil components (Iyamuremye and Dick, 1996). Dissolved organic carbon (DOC) isolated from field corn (*Zea mays* L.) and wheat (*Triticum aestivium* L.) residues decreased the rate of P sorption in a laboratory kinetics study (Ohno and Erich, 1997). Using an equilibrium sorption approach, Ohno and Crannell (1996) showed that DOC from hairy vetch (*Vivia villosa* L.) and crimson clover (*Trifolium incarnatum* L.) inhibited P sorption, while DOC from cattle manure (*Bos taurus*) and poultry manure (*Gallus domesticus*) did not inhibit P sorption. These studies show that DOC released from crop residues decrease P sorption, leading to greater soil P availability.

Soil organic matter has an important role in maintaining the productivity of soils. Studies have shown that changes in field management practices can alter the chemical properties of soil humic substances (Wander and Traina, 1996a,b; Zalba and Quiroga, 1999). Although it has been demonstrated that base-extracted humic substances are sensitive to management practices, there have been few studies investigating the DOC fraction of soils under different field management regimes. The labile nature of DOC results in this fraction being the most mobile and, presumably, the fraction most directly involved in reactions such as complexation with ions and the physico-chemical stabilization of soils (Zsolnay, 1996). Water-soluble DOC chemistry has been shown to be sensitive to different land use impacts in a natural fen (Kalbitz et al., 1999) and different litter species inputs in a woodland (Gressel et al., 1995).

Crop residue DOC (Ohno and Crannell, 1996; Ohno and Erich, 1997) and synthetic organic acids (Fox et al., 1990) have been shown to affect P soil chemistry in short reaction periods (<24 h) laboratory studies. Persistence of this action needs further studies along longer testing durations. In this study, we propose addressing effects of longer-term application of organic amendments on soil P chemistry from established cropping systems that have included animal- and green-manures. The specific objective is to investigate four different cropping systems for effects on the quantity and chemical characteristics of DOC isolated from the soils and the quantity–intensity relationships of soil P.

2. Materials and methods

2.1. Cropping system sites

Soils from four cropping system trials with 5–13 years of treatment history were collected and used in this study. Two of the systems, Potato Ecosystem (ECO) and Grass Fertility (GF), received animal manure in whole or as part of a set of organic rich amendments. The ECO site is in Presque Isle, Maine and the soil is classified as Caribou loam (fine-loamy, mixed, frigid, Typic Haplorthod) [World Reference Base (WRB) classification: Haplic Podzols]. A full description of study has been reported elsewhere (Gallandt et al., 1998). The study was started in 1990 and the soils were sampled in 2000. The organic amendment consisted of a pea (*Pisum sativum* L.), hairy vetch (*Vicia villosa* L. Roth), and oat (*Avena sativa* L.) green manure mixture, beef manure, and potato cull compost. The unamended control treatment used inorganic fertilizer. The GF site was located in Stillwater, Maine and the soil is classified as Lamoine silt loam (fine, illitic, nonacid, frigid Aeric Epiaquepts) [WRB classification: Stagnic Cambisols]. The study has been detailed in Griffin et al. (2002). The study was initiated in 1995 and the soils sampled in 2000. The organic matter amendment treatment consisted of liquid dairy manure and the control received no nutrient applications.

The Liebman E Rotation (LER) located in Stillwater, Maine and the Porter Rotation (PR) located in Presque Isle, Maine received green manure as the organic amendment. The LER study was initiated in 1990 and the soils sampled in 2000. The soil type was a Nicholville very fine sandy loam (0–2% slope, coarse-silty, mixed, frigid, Aquic Haplorthods) [WRB classification: Gleyic Cambisols] and the study has been detailed in Davis and Liebman (2001) and Liebman and Gallandt (2002). Soils were sampled from the wheat plus red clover (*Trifolium pratense* L.) (amended) and the wheat (control) plots. The amendment treatment received a small single application of composted dairy manure in 1997 which because it occurred 3 years prior to soil sampling, the classification of this as a green manure cropping system is justified. The PR study was initiated in 1987 and the soils sampled in 2000. The soil type was a Caribou gravelly loam soil (fine-loamy, isotic, frigid, Typic Haplorthods) [WRB classification: Haplic Podzols]. Soils sampled from the PR study were from the PVO green manure (amended) mixture and the oat (control) plots. The details of this study have been reported in Plotkin (2000). Further details of the soils used have been reported in Grffin and Porter (2004).

2.2. Soil chemical characterization

Soil samples collected from three replications of each soil treatment from the four studies were air dried and ground to pass a 2-mm screen. Olsen P was determined by adding 20 mL of 0.5 mol L^{-1} $NaHCO_3$, pH 8.5 extractant to 1.00 g of soil, shaking for 30 min, and filtering through Whatman 42 filter paper (Kuo, 1996). Water-soluble P was determined by adding 10 mL of deionized-distilled water (DI-H_2O) to 1.00 g of soil and shaking for 2 h in 15 mL centrifuge tubes followed by centrifugation for 30 min at 900 × *g* and filtered through Whatman 42 filter paper. The P in both sets of solutions was determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Total soil P was determined using microwave digestion (Kuo, 1996).

Phosphorus quantity/intensity (Q/I) isotherms were obtained by adding 10 mL of solution containing 0.25, 0.50, 1.00, 2.00, and 4.00 mg L^{-1} P to 0.40 g of soil in 15 mL centrifuge tubes. The suspensions were shaken for 24 h, centrifuged, and then vacuum filtered through 0.4 μm membrane filters. The P concentration was determined by ICP-AES. The quantity of P desorbed or adsorbed was calculated from the change in concentration from the initial solution added. The Q/I diagrams were obtained by plotting the quantity desorbed or adsorbed (ΔP) on the *Y*-axis as a function of the equilibrium P concentration on the *X*-axis. The slope of the regression lines is the equilibrium buffering capacity (EBC), which relates to the ability of the soil to replenish the soil solution P as it is removed via plant uptake. The *Y*-axis intercept represents the estimated labile-P content of the soil and the *X*-axis intercept represents equilibrium P concentration (EPC). The values of the three replicates were averaged and the linear regression was used to determine Q/I parameters.

2.3. Extraction and spectral characterization of DOC

Soil DOC was extracted by adding 10.0 mL of deionized-H_2O to 1.00 g of soil in a 50 mL centrifuge tube. The suspension was shaken on an orbital shaker for 30 min at room temperature (22 ± 1 °C), centrifuged at 900 × *g* for 30 min, and filtered through 0.45 μm Acrodisk syringe filters. The extraction period was selected to minimize microbial DOC alteration during extraction (Zhou and Wong, 2000). The DOC concentration of the extracts were determined using a Shimadzu 5000 analyzer. Total soil C was determined using a LECO carbon analyzer.

Ultraviolet-visible absorption spectra of the extracts from 200 to 500 nm were obtained using an Agilent 8453 diode-array spectrophotometer and a 1 cm quartz cuvette. Fluorescence measurements were obtained using a Hitachi F-4500 spectrofluoremeter. Instrumental parameters were excitation (EX) and emission (EM) slits, 5 nm; response time, 8 s; and scan speed 240 nm min^{-1}. The EM spectra were obtained by using 254 nm for EX and EM recorded from 280 to 500 nm. Fluorescence intensity values are relative to the instrument conditions at the time of measurement and are a function of source intensity, optical efficiency, and detector efficiency. The sensitivity and stability of the instrument was measured using the Raman band signal intensity (EX, 350 nm; EM, 397 nm). The Raman band intensity was determined prior to each sample and the fluorescence intensities were divided by the Raman intensity to correct for any fluctuations in instrumental conditions. The humification index (HIX) was determined using inner-filtering corrected fluorescence emission spectra:

$$\mathrm{HIX} = \frac{\Sigma I_{435 \to 480}}{\Sigma I_{300 \to 345}} \qquad (1)$$

where I is the fluorescence intensity at each wavelength (Ohno, 2002).

2.4. Statistical analysis

All data were analyzed at an alpha level of 0.05 or 0.10 in a completely randomized design model using the analysis of variance module of Systat for Windows, Version 10.2 (Point Richmond, CA, U.S.A.). All treatment means were separated using Fisher's protected least significant difference (LSD) mean separation in Systat.

3. Results and discussion

3.1. Cropping systems effects on soil organic matter

The C stock present in the soils at the 2000 sampling date, assuming a 20 cm plough depth and bulk density of 1.2 g cm^{-3}, at the four study sites are: 38,400; 45,600; 47,500; and 49,000 kg C ha^{-1} for ECO, GF, LER, and PR, respectively. The corresponding estimated differences in annual C input between the organic amendment treatment and the non-amended control calculated from the C content of the amendment materials and the loading rate for the cropping studies were: 8100; 1010; 1080 and 415 kg C ha^{-1} year^{-1}.

The addition of organic amendments significantly increased both total soil C and DOC content for the animal manure based ECO study at the $P < 0.05$ level and the GF study at the $P < 0.10$ level, while no significant treatment effects on total C were found for the legume-based LER and PR studies (Table 1). The lack of statistically significant effect in total C content of the soils in the legume-based systems (LER and PR) is expected considering the relatively low amounts added to the soils as compared to the soil C present. The ECO study had quantity differences between the organic matter amendment and control plots that were 8 to 20 times greater than in the other three tested systems. The large difference in C amendment loading

Table 1
Total C and dissolved organic carbon content of the Potato Ecosystems (ECO), Grass Fertility (GF), Liebman E Rotation (LER), and Porter Rotation (PR) cropping system study soils

Cropping study	Treatment	Total C (g kg^{-1})	Dissolved organic carbon (g kg^{-1})
ECO	+OM[a]	22.2	0.226
	−OM	16.0	0.175
GF	+OM	22.7	0.279
	−OM	19.0	0.250
LER	+OM	19.2	0.130
	−OM	19.8	0.126
PR	+OM	20.7	0.181
	−OM	20.4	0.178
ANOVA[b]		P	
CSS		0.594	0.001
TRT		0.036	0.028
CSS TRT		0.118	0.224
	$LSD_{0.05}$	4.4	0.039
	$LSD_{0.10}$	3.6	0.029

[a] OM: organic matter amendment.
[b] CSS: cropping study system; LSD: least significant difference; TRT: organic amendment treatment.

probably caused the increased total soil C content found in the ECO study (Table 1). However, the ability of the manure-based GF study to increase the total C levels ($P < 0.10$) with approximately the same C input level as in the case of LER suggests that the beef manure is less likely to undergo decomposition than the green manure probably due to differences in the chemical nature of organic matter ligands released from the two types of materials.

It is interesting to note that although there was no significant effect ($P = 0.59$) of cropping systems on total C content, there was a very strong cropping systems effect ($P = 0.001$) on DOC content (Table 1). The DOC fraction of soil organic matter is the most labile in soils and believed to be the fraction that is most reactive in soil solution (Zsolnay, 1996). The results of this study (Table 1) suggest that DOC content of soils is strongly influenced by the soil chemical, physical, and biological conditions of the particular sites under investigation even though they were similar in total C content.

3.2. Cropping systems effects on dissolved organic matter spectral characteristics

Data shown in Table 2 indicates increasing degree of organic matter humification with greater HIX values and lower E2/E3 values. The HIX values did not significantly change by the addition of organic amendments for the cropping systems studied (Table 2). However, the E2/E3 ratio did record a significant ($P < 0.05$) increase in humification to application of organic amendment treatment for the ECO study, which indicates that the addition of manure amendment resulted in a more humified soil DOC fraction.

Table 2
Humification index (HIX) and E2/E3 ratio for the dissolved organic matter extract of the Potato Ecosystems (ECO), Grass Fertility (GF), Liebman E Rotation (LER), and Porter Rotation (PR) cropping system study soils

Cropping study	Treatment	HIX	E2/E3
ECO	+OM[a]	7.29	4.85
	−OM	6.86	5.21
GF	+OM	5.14	5.38
	−OM	5.17	5.53
LER	+OM	5.79	5.29
	−OM	5.76	5.34
PR	+OM	6.24	5.15
	−OM	6.66	5.11
ANOVA[b]		*P*	
CSS		0.000	0.005
TRT		0.984	0.092
CSS TRT		0.374	0.304
	$LSD_{0.05}$	0.70	0.32

[a] OM: organic matter amendment.
[b] CSS: cropping study system; LSD: least significant difference; TRT: organic amendment treatment.

Increasing degree of humification was found to alter organic matter nature by increasing total exchangeable acidity, carboxyl group content, and N-containing functional group content (Stott and Martin, 1990), which in turn should enhance organic matter interaction with both ionic constituents in solution and mineral surfaces (Sposito, 1989). The results suggest that differences in the chemical properties of the manure-derived organic matter from the ECO study may play a role in the increases in the level of total and dissolved organic matter. Similar to the results for DOC content of the soils, both HIX and E2/E3 parameters were significantly affected in the ECO study. This suggests that the nature of the dissolved organic matter found in soils, as well as the quantity, is dependent on the soil environmental characteristics of the site. The findings from the study of the organic matter in these cropping systems show that animal manure application has greater potential to alter both the quantity of organic matter present in the soils as well as the chemical structural properties of the organic matter.

3.3. Phosphorus soil tests

Standard soil testing methodologies were used to determine the effects of organic matter amendment on soil P parameters. The quantity of total P, Olsen-P, and water soluble-P in the soils are shown in Table 3. The total P content varied widely among the different cropping systems due to different management histories and practices. There were no amendment effects on total P and Olsen soil test P indicating that the addition of organic materials to the soil did not affect the total P and the chemically extractable soil P pools (Table 3). The P_{WS} concentration in the 1:10 extract was significantly affected by the organic amendments ($P < 0.05$, Table 3). Similar to the trends of changes of the total C and DOC, only the ECO cropping practice showed statistically significant

Table 3
Total P, Olsen soil test P, and water soluble P contents of the Potato Ecosystems (ECO), Grass Fertility (GF), Liebman E Rotation (LER), and Porter Rotation (PR) cropping system study soils

Cropping study	Treatment	Total P (mg kg^{-1})	Olsen P (mg kg^{-1})	P_{WS} (mg kg^{-1})
ECO	+OM[a]	1670	97.3	11.2
	−OM	1570	89.3	7.14
GF	+OM	680	48.1	10.9
	−OM	670	44.8	9.15
LER	+OM	820	27.9	1.48
	−OM	830	29.1	1.55
PR	+OM	1140	72.5	5.02
	−OM	1130	74.6	5.26
ANOVA[b]		*P*		
CSS		0.000	0.001	0.000
TRT		0.680	0.585	0.046
CSS TRT		0.952	0.728	0.099
	$LSD_{0.05}$	310	14.9	2.67

[a] OM: organic matter amendment.
[b] CSS: cropping study system; LSD: least significant difference; TRT: organic amendment treatment.

change with the organically amended plots having higher P_{WS} levels than the unamended control ones.

Previous laboratory studies have shown that DOC isolated from crop residues reduce the quantity of P sorbed by soils as well as the rate of the P sorption (Ohno and Crannell, 1996; Ohno and Erich, 1997). The results of the study would suggest that DOC levels in soils would be indicative to P-solubility in field soils. The relationship between P_{WS} (Table 3) and DOC (Table 1) pooled across all four cropping studies was found to be highly significant (r^2 = 0.86, P < 0.001, n = 8), supporting the contention that DOC concentration can be helpful in estimating the concentration of P_{WS} in soils (Fig. 1).

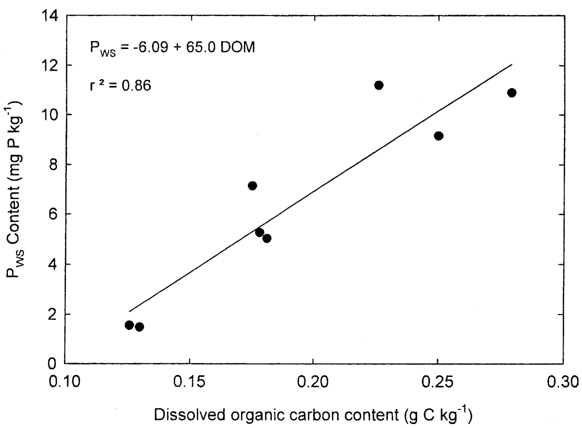

Fig. 1. Relationship between water-soluble phosphorus (P_{WS}) concentration and dissolved organic carbon (DOC) concentration in 1:10 soil:water extracts from the four cropping systems.

3.4. Phosphorus quantity/intensity relationships

In comparison to standard soil P tests, the Q/I methodologies have been proposed as a more mechanistic approach to determining P availability in soils (Hartikainen, 1991; Kpomblekou-A and Tabatabai, 1997). The Q/I isotherms results are shown in Fig. 2 for the manure based ECO and GF cropping studies and in Fig. 3 for the green manure based LER and PR rotation studies. Linear regression of all the treatments shown in Figs. 2 and 3 fit the data well with r^2 > 0.97. The calculated values for ΔP, EBC, and EPC are shown in Table 4. In accordance with the results discussed previously, the ECO system was the only one where the addition of organic rich amendment significantly affected the soil P buffering power and equilibrium P concentration. Addition of the amendment increased the labile P content of soils in both the ECO and GF manure-based systems.

3.5. Phosphorus uptake simulation modeling

The uptake of nutrients from soils has been comprehensively investigated by Barber and Nye with their co-workers (Barber, 1995; Tinker and Nye,

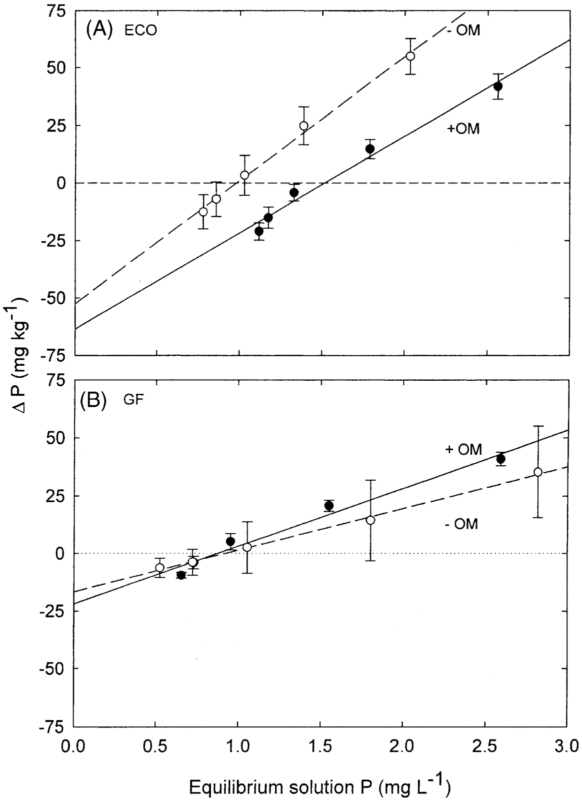

Fig. 2. Phosphorus quantity/intensity relationships of the soils from the animal manure based ECO (A) and GF (B) cropping systems. Error bars represent standard deviation of the mean.

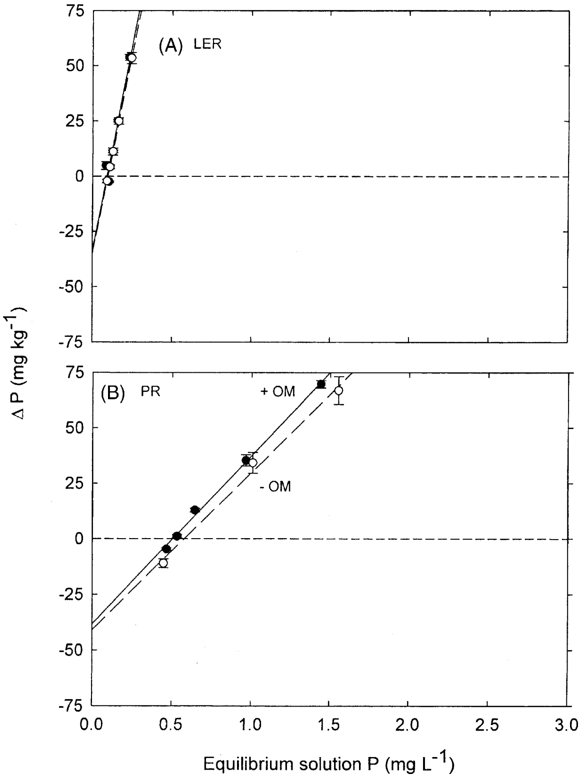

Fig. 3. Phosphorus quantity/intensity relationships of soils from legume based LER (A) and PR (B) cropping system studies. Error bars represent standard deviation of the mean.

2000). Claassen and Barber (1976) and Barber (1995) demonstrated that mechanistic simulation modeling of P uptake can successfully indicate the availability to plants of P in soils. The Cushman–Barber Nutrient Uptake Model Version 3.3 (Barber, 1995) was used to elucidate to what extent the cropping system amendment treatments can affect the P availability of the soils. The model calculates nutrient uptake by determining transport and concentration of the nutrient at the root:soil interface (the supply of nutrients to the roots) and uptake rate at the calculated nutrient concentration (the demand of nutrients by the roots) as the root system grows. Our intent was not to compare predicted P uptake to actual P uptake in a bioassay study, but rather to use the simulation model as a tool to evaluate how the differences in soil P characteristics, such as P buffering power and equilibrium soil P concentration in the cropping systems may affect soil P availability.

The required general experimentally determined parameters for this exercise are the concentration of the nutrient in bulk soil solution, the buffer power of the nutrient, and the effective soil diffusion coefficient of the nutrient. Phosphorus concentration in bulk soil solution was estimated by P_{WS} (Table 3). The EBC was used to estimate the P buffering power of the soil (Table 4). The soil diffusion coefficient is the remaining soil parameter needed to mechanistically model P uptake. Vaidyanathan et al. (1968) reported that the diffusion coefficient of an ion in soil can be expressed as

$$D_s = \frac{f_l \theta_l D_l}{b} \tag{2}$$

where D_s is the diffusion coefficient in soil, f_l the tortuosity of the soil, f_l the water content expressed as a fraction of soil volume, D_l the diffusion coefficient of the nutrient in liquid water, and b is the buffering

Table 4
Phosphorus quantity/intensity isotherm derived parameters and calculated soil diffusion coefficient of the Potato Ecosystems (ECO), Grass Fertility (GF), Liebman E Rotation (LER), and Porter Rotation (PR) cropping system study soils

Cropping system study	Treatment	Labile P (mg P kg^{-1})	EPC[a] (mg P L^{-1})	EBC[a] (L kg^{-1})	Soil diffusion coefficient
ECO	+OM[b]	-63.7 ± 5.5[*]	1.51 ± 0.18[*]	42.0 ± 3.3[*]	6.40×10^{-9}
	−OM	-52.6 ± 2.9	0.98 ± 0.07	53.7 ± 2.2	6.40×10^{-9}
GF	+OM	-21.8 ± 3.6[*]	0.87 ± 0.16 NS	25.1 ± 2.4 NS	1.08×10^{-8}
	−OM	-16.6 ± 1.0	0.92 ± 0.06	18.1 ± 0.6	1.89×10^{-8}
LER	+OM	-34.1 ± 7.9 NS	0.091 ± 0.025 NS	374 ± 53 NS	8.17×10^{-10}
	−OM	-35.0 ± 0.5	0.096 ± 0.010	363 ± 30	7.57×10^{-10}
PR	+OM	-38.4 ± 2.1 NS	0.51 ± 0.032 NS	75.4 ± 2.4 NS	3.57×10^{-9}
	−OM	-37.9 ± 2.9	0.55 ± 0.048	68.5 ± 2.8	3.94×10^{-9}

NS designates no significant differences between treatment and unamended control.
[a] EPC: equilibrium phosphorus concentration; EBC: equilibrium buffering capacity.
[b] OM: organic matter amendment.
[*] Designates significant difference in slope of the regression line between the treatment and control regression lines at the $P < 0.05$ level.

power. Calculated values for D_s were obtained for the cropping system soils by using a f_l value of 0.15 (Warncke and Barber, 1972), a θ_l value of 0.20 (Schenk and Barber, 1979), a D_l value of 0.89×10^{-5} $cm^2\ s^{-1}$ (Schenk and Barber, 1979), and the derived EBC values (Table 4).

The plant component of the Cushman–Barber model uses Michaelis–Menten kinetics to describe the relationship between concentration of the nutrient at the root:soil interface and uptake rate. These parameters are typically obtained in solution-culture studies. Parameters are also required for the root growth rate and root radius. The remaining variables were fixed for the root morphological characteristic parameters and root P uptake kinetics: water flux, 5×10^{-7} cm s^{-1}; half distance between root axis, 0.33 cm; root radius, 0.015 cm; initial root length, 250 cm; root growth rate, 3.9×10^{-6} cm s^{-1}; maximal influx, 6×10^{-7} μmol cm^{-1} s^{-1}; Michaelis–Menten constant, 5.00×10^{-3} mol cm^{-1}; and concentration where influx is zero, 2×10^{-4} mol cm^{-1}.

The simulation runs predicted that the P uptake would be significantly greater ($P < 0.05$) for the two animal manure based cropping systems, ECO and GF, but not for the legume based LER and PR studies (Fig. 4). This simulation adds additional evidence that manure-based amendments can increase soil P bioavailability as compared to green manure by altering the P soil chemistry. Sensitivity analysis for P uptake by the Cushman–Barber model (Silberbush and Barber, 1983) showed that P uptake was very sensitive to the P concentration in bulk soil solution concentration. The sensitivity of P availability to P concentration in soil solution highlights the importance and significance of the ability of manure amendment to increase DOC and P_{WS} concentrations, and consequently, P bioavailability to plants (Tables 1 and 3; Fig. 1).

It is interesting to note that a previous laboratory study showed that DOC from cover crops did inhibit P sorption to soils, but DOC isolated from animal manures did not inhibit P sorption (Ohno and Crannell, 1996). The reversal of the effects of animal and legume derived DOC may be due to differing time

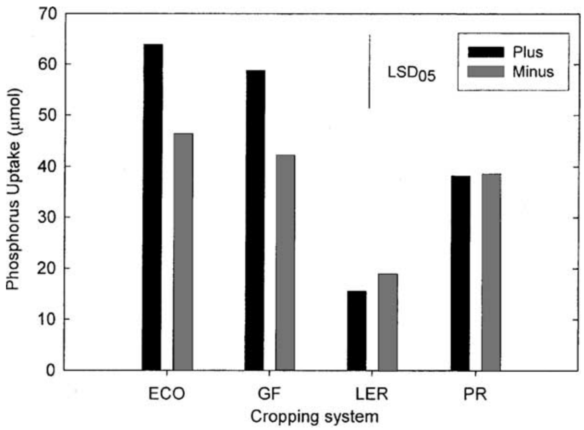

Fig. 4. Predicted phosphorus uptake for the control and amended treatments from four cropping systems using the mechanistic Cushman–Barber nutrient uptake model. Bar represents the least significant difference at the P = 0.05 level.

scales of the two studies. The short-term effects of the laboratory study working with DOC derived directly from the manure and legume sources may not reflect the long-term effects. One possible reason for the reversal of effects is that the short-term laboratory effects are dominated by short-lived, transitory soluble organic matter while the long-term effects are determined by more refractory fraction of soluble organic matter that is formed after microbial resynthesis of the initially released material.

4. Conclusion

The results of this study suggests that addition of animal manures may increase the bioavailability of soil P by increasing the concentration of soil DOC. The use of crop management systems which uses animal manure can be beneficial from an agronomic perspective by decreasing the requirement for inorganic fertilizer to meet crop demand. The practice of landspreading animal manure also assists in the environmental issue of animal manure disposal. Further research is warranted to explain the mechanisms by which animal manure may increase P bioavailability. This would help resolve the question of the differential results obtained from short and long term experiments on animal and green manure application on soil DOC and P bioavailability.

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References

Barber, S.A., 1995. Soil Nutrient Bioavailability: A Mechanistic Approach, second ed. Wiley, New York.

Claassen, N., Barber, S.A., 1976. Simulation model for nutrient uptake from soil by a growing plant root system. Agron. J. 68, 961–964.

Davis, A.S., Liebman, M., 2001. Nitrogen source influences wild mustard growth and competitive effect on sweet corn. Weed Sci. 49, 558–566.

Fox, T.R., Comerford, N.B., McFee, W.W., 1990. Phosphorus and aluminum release from a spodic horizon mediated by organic acids. Soil Sci. Soc. Am. J. 54, 1763–1767.

Gallandt, E.R., Mallory, E.B., Alford, A.R., Drummond, F.A., Groden, E., Liebman, M., Marra, M., McBurnie, J.C., Porter, G.A., 1998. Comparison of alternative pest and soil management strategies for Maine potato production systems. Am. J. Alt. Agric. 13, 146–161.

Gressel, N., Inbar, Y., Singer, A., Chen, Y., 1995. Chemical and spectroscopic properties of leaf litter and decomposed organic matter in the Carmel Range. Israel Soil Bio. Biochem. 27, 23–31.

Grffin, T.S., Porter, G.A., 2004. Altering soil carbon and nitrogen stocks in intensively tilled two-year rotations. Biol. Fertil. Soils 39, 366–374.

Griffin, T., Giberson, E., Wiedenhoeft, M., 2002. Yield response of long-term mixed grassland swards and nutrient cycling under different nutrient sources and management regimes. Grass Forage Sci. 57, 1–11.

Hartikainen, H., 1991. Potential mobility of accumulated phosphorus in soil as estimated by the indices of Q/I plots and by extractant. Soil Sci. 152, 204–209.

Iyamuremye, F., Dick, R.P., 1996. Organic amendments and phosphorus sorption by soils. Adv. Agron. 56, 139–185.

Higgs, B., Johnston, A.E., Salter, J.L., Dawson, C.J., 2000. Some aspects of achieving sustainable phosphorus use in agriculture. J. Environ. Qual. 29, 80–87.

Kalbitz, K., Geyer, W., Geyer, S., 1999. Spectroscopic properties of dissolved humic substances – a reflection of land use history in a fen area. Biogeochemistry 47, 219–238.

Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. Adv. Agron. 53, 1–45.

Kpomblekou-A, K., Tabatabai, A., 1997. Effect of cropping systems on quantity/intensity relationships of soil phosphorus. Soil Sci. 162, 56–68.

Kuo, S., 1996. Phosphorus. In: Sparks, D.L. (Ed.), Methods of Soil Analysis: Chemical Methods, Part 3. SSSA, Madison, WI, pp. 869–919.

Liebman, M., Gallandt, E.R., 2002. Differential responses to red clover residue and ammonium nitrate fertilizer by common bean and wild mustard. Weed Sci. 50, 521–529.

Lindsay, W.L., 1979. Chemical Equilibria in Soils. Wiley, New York.

Ohno, T., 2002. Fluorescence inner-filtering correction for determining the humification index of dissolved organic matter. Environ. Sci. Technol. 36, 742–746.

Ohno, T., Crannell, B.S., 1996. Green and animal manure-derived dissolved organic matter effects on phosphorus sorption. J. Environ. Qual. 25, 1137–1143.

Ohno, T., Erich, M.S., 1997. Inhibitory effects of crop residue-derived organic ligands on phosphate adsorption kinetics. J. Environ. Qual. 26, 889–895.

Plotkin, J.M., 2000. The effects of green manure rotation crops on soil and potato yield and quality. M.S. Thesis, University of Maine.

Schenk, M.K., Barber, S.A., 1979. Phosphate uptake by corn as affected by soil characteristics and root morphology. Soil Sci. Soc. Am. J. 43, 880–883.

Sharpley, A.N., Foy, B., Withers, P.J.A., 2000. Practical and innovative measures for the control of agricultural phosphorus losses to water: an overview. J. Environ. Qual. 29, 1–9.

Silberbush, M., Barber, S.A., 1983. Sensitivity of simulated phosphorus uptake to parameters used by mechanistic-mathematical model. Plant Soil 74, 93–100.

Sposito, G., 1989. Chemistry of Soils. Oxford University Press, New York.

Stott, D.E., Martin, J.P., 1990. Synthesis and degradation of natural and synthetic humic material in soil. In: MacCarthy, P., Clapp, C.E., Malcolm, R.L., Bloom, P.R. (Eds.), Humic Substances in Soil and Crop Science: Selected Readings. ASA-SSSA, Madison, WI, pp. 37–63.

Tinker, P.B., Nye, P.H., 2000. Solute Movement in the Rhizosphere. Oxford University Press, New York.

Tisdale, S.J., Nelson, W.L., Beaton, J.D., Havlin, J.L., 1993. Soil Fertility and Fertilizers, fifth ed. Macmillan, New York.

USEPA, 1996. Environmental indicators of water quality in the United States. EPA 841-R-96-002. USEPA, Office of Water (4503F), U.S. Government Print. Office, Washington, DC.

Vaidyanathan, L.V., Drew, M.C., Nye, P.H., 1968. The measurement and mechanism of ion diffusion in soils. IV. The concentration dependence of diffusion coefficients of potassium in soils at a range of moisture levels and a method for the estimation of the differential diffusion coefficient at any concentration. J. Soil Sci. 19, 94–107.

Wander, M.M., Traina, S.J., 1996a. Organic matter fractions from organically and conventionally managed soils. I. Carbon and nitrogen distributions. Soil Sci. Soc. Am. J. 60, 1081–1087.

Wander, M.M., Traina, S.J., 1996b. Organic matter fractions from organically and conventionally managed soils. II. DR-FTIR characterization composition. Soil Sci. Soc. Am. J. 60, 1087–1094.

Warncke, D.D., Barber, S.A., 1972. Diffusion of zinc in soil. I. The influence of soil moisture. Soil Sci. Soc. Am. Proc. 36, 39–42.

Zalba, P., Quiroga, A.R., 1999. Fulvic acid carbon as a diagnostic feature for agricultural soil evaluation. Soil Sci. 164, 57–61.

Zhou, L.X., Wong, J.W.C., 2000. Microbial decomposition of dissolved organic matter and its control during a sorption experiment. J. Environ. Qual. 29, 1852–1856.

Zsolnay, A., 1996. Dissolved humus in soil waters. In: Piccolo, A. (Ed.), Humic Substances in Terrestrial Ecosystems. Elsevier, Amsterdam, pp. 171–223.